Space Geodesy Project

NASA Sponsored International Activities in Support of Space Geodesy

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1.0	12/18/12	Initial release.	All

1 Introduction

This document presents the space-based geodesy activities that NASA is currently supporting in the domestic and international arenas. These activities constitute NASA's strategic response to present and future national needs for critical geodetic products and services, as outlined in recent National Research Council reports[1].

1.1 Document overview

Points of contact for this report are provided in Section 1.2. An executive summary of NASA's activities in support of space geodesy is presented in Section 2. Specific space-based geodesy activities are presented in Section 3. The section includes the background containing the rationale for this support in Section 3.1, NASA's support of the global geodetic observation systems in Section 3.2, and NASA's support of specific geodetic techniques and products utilized and delivered by observation systems in Section 3.3. The contributors to this report are acknowledged in Section 4.0.

1.2 Points of contact

Table 1.2-1 shows the points of contact for the different areas covered in this report.

Activity/Sub-Activity	POC	Affiliation	e-mail
GGOS/Coordination	Ruth Neilan	NASA JPL	ruth.e.neilan@jpl.nasa.gov
GGOS/Science	Richard Gross	NASA JPL	richard.s.gross@jpl.nasa.gov
SGP	Stephen Merkowitz	NASA GSFC	stephen.m.merkowitz@nasa.gov
IERS	Chopo Ma	NASA GSFC	chopo.ma-1@nasa.gov
VLBI	Dirk Behrend	NASA GSFC	dirk.behrend-1@nasa.gov
SLR	Michael Pearlman	Harvard-Smithsonian	mpearlman@cfa.harvard.edu
GNSS	Ruth Neilan	NASA JPL	ruth.e.neilan@jpl.nasa.gov
DORIS	Frank Lemoine	NASA GSFC	frank.g.lemoine@nasa.gov
CDDIS	Carey Noll	NASA GSFC	carey.e.noll@nasa.gov

Table 1.2-1: Points of contact for this report

[1] *"Precise Geodetic Infrastructure, National Requirements for a Shared Resource"*, National Research Council, The National Academies Press, 2010. Henceforth referred to as the "NRC's National Requirements".

2 Executive Summary

NASA efforts in support of space-based geodesy have been, and continue to be, strategically aligned with the recommendations put forward by the National Research Council. These recommendations were produced at the request of NASA and other federal agencies, including the National Oceanic and Atmospheric Administration (NOAA), the National Environmental Satellite Data and Information Service (NESDIS), and the U.S. Geological Survey (USGS), in order to create a consistent policy. These activities play a key role in supporting NASA's space missions and their scientific objectives as well as supporting the national geodetic infrastructure as a whole.

> **"NASA's activities in support of space-based geodesy are strategically aligned with the direction provided by the National Research Council"**

NASA's efforts are also aligned with the international initiative to deploy the next generation of the Global Geodetic Observing System[2]. This global observation system seeks to provide the geodetic observing infrastructure that will answer key scientific questions—including climate change—affecting society. It also aims to pragmatically provide the information needed to guide policy making and natural disaster risk management. Due to the global nature of space-based geodesy, NASA's activities and leadership require an international dimension in order to be successful.

> **"These activities are essential to support NASA's space missions and their scientific objectives, as well as to support the critical national geodetic infrastructure"**

NASA's activities in space-based geodesy can be classified into two logical groups: The first encompasses the efforts related to the next generation of geodetic observing systems; and the second addresses the activities related to the individual observation techniques that comprise the observation systems, as well as the generation of key products. This first group of activities includes NASA's development of next-generation of observation techniques. Let us summarize some key points:

- Under the NASA Space Geodesy Project, a pioneering next-generation geodetic observation system is taking shape. Activities include engineering and fieldwork relating to the realization of the first prototype fundamental geodetic site that employs the next-generation of VLBI, SLR, GNSS and DORIS instruments, combined.
- NASA leadership shapes the future of the Global Geodetic Observing System (GGOS), where NASA's Space Geodesy System (developed under SGP) plays a trailblazing role and will serve as NASA's contribution to this global network.
- All space-based geodesy techniques (VLBI, SLR, GNSS, DORIS) and product-oriented combination centers, like the International Earth Rotation and Reference Systems Service (IERS), benefit from NASA leadership. NASA personnel hold major positions in all related international services, their committees, and working groups. NASA's technical, managerial and intellectual contributions are significant in these international forums.

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[2] *Global Geodetic Observing System*, May 2012, http://www.ggos.org/

- NASA scientists and engineers continue to develop the next-generation of geodetic observing techniques, namely VLBI, SLR, GNSS and DORIS, including the development of techniques for collective and faster processing of these techniques. This includes the evolution to real-time data and products—like in the case of GNSS—critical to the mitigation and response to geo-hazards.
- The Crustal Dynamics Data Information System (CDDIS) is the only data center providing archive and distribution support to all four geometric services of the International Association of Geodesy (IAG) as well as GGOS.

3 NASA's Support of Space Geodesy Activities

3.1 Background

"The United States […], as a matter of national security, should invest in maintaining and improving the geodetic infrastructure"

The National Research Council issued two seminal reports in recent years (2007 and 2010 respectively):

- *"Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond".* [3]
- *"Precise Geodetic Infrastructure, National Requirements for a Shared Resource".*[4]

The first report, known as the "Decadal Survey", was the NRC response to the requests of NASA and other agencies to generate a consensus of recommendations from the Earth and environmental science and applications communities regarding: (1) high-priority flight missions and activities to support national needs for research and monitoring of the dynamic Earth system during the next decade, and (2) important directions that should influence planning for the decade beyond[5]. The NRC recommended that: *"The U.S. government, working in concert with the private sector, academe, the public, and its international partners, should renew its investment in Earth-observing systems and restore its leadership in Earth science and applications."*[6] The NRC then recommended that a number of critical NASA (and NOAA) earth observing missions take place over the next decade. These missions have a common denominator in the need for an accurate and stable International Terrestrial Reference Frame (ITRF) that enables the precise location of the spacecraft and their scientific instruments. This, in turn, allows the unambiguous referencing of all scientific data from plate-tectonic displacements to sea-surface height, establishing a key link between the geodetic infrastructure and the space missions.

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[3] *"Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond"*, [a.k.a. "the Decadal Survey], National Research Council, The National Academies Press, 2007.
[4] *"Precise Geodetic Infrastructure, National Requirements for a Shared Resource"*, National Research Council, The National Academies Press, 2010.
[5] *"Decadal Survey",* op. cit. p. 1.
[6] *"Decadal Survey",* op. cit. p. 2.

The second cited report from the NRC addressed the precarious state of the critical national geodetic[7] infrastructure, and recommended that: *"The United States, to maintain leadership in industry and science, and as a matter of national security, should invest in maintaining and improving the geodetic infrastructure, through upgrades in network design and construction, modernization of current observing systems, deployment of improved multi-technique observing capabilities, and funding opportunities for research, analysis, and education in global geodesy."*[8] In its present form, the geodetic observing system infrastructure is quickly deteriorating, and products such as an accurate and stable ITRF are in jeopardy. This deterioration is impeding current infrastructure from being able to meet the new, more stringent science requirements needed to support the key scientific questions connected to societal challenges.

"Observing systems, like the one responsible for realizing the ITRF, expand beyond national boundaries; NASA's support of these activities also must expand internationally."

NASA's space-based geodesy activities are strategically aligned with the imperative national requirements set forth by the National Research Council as outlined in these two previously cited reports. Because a geodetic observing system, like the one necessary to realize the International Terrestrial Reference Frame[9], expands beyond national borders, NASA's support of these activities also must expand internationally. In other words, NASA's national support for space-based geodesy must expand overseas in order to be effective. Details of these activities and their relationship to the overarching NRC report recommendations are presented in the next section.

[7] The science of geodesy concerns itself with the accurate measurement and understanding of the Earth's geometric shape, its orientation in space, its gravity field and the variation of these parameters in time. "NRC National Requirements", op. cit. p. 3.

[8] "NRC's National Requirements", op. cit. p. 3.

[9] *International Terrestrial Reference Frame*, May 2012, http://itrf.ensg.ign.fr/

3.2 NASA Activities Supporting Space-Based Geodesy

The following section described NASA's activities in support of space-based geodesy.

3.2.1 NASA's Space Geodesy Project and the Global Geodetic Observing System

National Research Center Recommendation

"In the long term, the United States should deploy additional stations to complement and increase the density of the international geodetic network, in a cooperative effort with its international partners, with a goal of reaching a global geodetic network of at least 24 fundamental stations."

[NRC's National Requirements, p. 6, p.96 & p. 104.]

"The United States should establish a federal geodetic service to coordinate and facilitate the modernization and long-term operation of the national and global precise geodetic infrastructure to ensure convenient, rapid, and reliable access to consistent and accurate geodetic data and products by government, academic, commercial, and public users."

[NRC's National Requirements, pp. 7-8 & p. 109.]

NASA's Activities in Support of this Objective

The Global Geodetic Observing System (GGOS) initiative and the Space Geodesy Project (SGP)—see text box—are both a direct response to the first recommendation of the NRC. SGP, under the leadership of NASA, also serves as a preliminary step in the formulation of a federal geodetic service as stated in the second NRC recommendation above.

- **Global Geodetic Observing System (GGOS)**

  *NASA's Leading Role in GGOS—*NASA plays a leading role in GGOS, and has done so from the beginning. GGOS was established by the IAG in 2003 as a *project*, becoming a full *Component of the IAG* in 2007. During this time, four of the six original members of the GGOS Executive Committee were

GGOS & SGP

The Global Geodetic Observing System (GGOS) of the International Association of Geodesy (IAG) is the umbrella under which the IAG Services and Commissions are unified into a complex integrated observing system that is being used to address relevant geodetic, geodynamical and geophysical problems having a deep impact on vital issues for humankind. We are faced today with the many challenges of global change and increasing vulnerability to natural disasters that require both response and risk mitigation. GGOS and the IAG Services and Commissions provide a vital link between scientific research, observations, analysis, modeling, and decision support for policy makers.

The Space Geodesy Project (SGP) oversees the formulation and development of the U.S. component of GGOS.

supported by NASA (C. Ma, R. Neilan, M. Pearlman, H.-P. Plag) including two of the founding Vice-Chairs, R. Neilan and H.-P. Plag; Five of the twelve members of the Science Panel were supported by NASA (A. Donnellan, R. Gross, M. Rodell, J. Wahr, V. Zlotnicki) including the Chair of the Science Panel, R. Gross; and participation in the GGOS Bureaus, Working Groups, and Themes were supported by NASA including the Director of the Bureau for Networks and Communication, M. Pearlman, and the Co-Chair of the Working Group on Data and Information Systems, C. Noll.

*NASA's Authors of GGOS's Book—*NASA also supported the preparation of the GGOS 2020 reference document "*Global Geodetic Observing System: Meeting the Requirements of a Global Society on a Changing Planet in 2020."* Both editors of the book, H.-P. Plag and M. Pearlman, were supported by NASA, as were four of the nine lead authors (R. Gross, T. Herring, H.-P. Plag, J. Zumberge) and 23 of the 57 contributing authors. This book served as the initial basis for the implementation of GGOS and is used to derive work plans based upon its recommendations.

*NASA's Leadership in GIAC—*The Chair of the GGOS Inter-Agency Committee (GIAC), J. LaBrecque, is from NASA. The GIAC is composed of representatives of governmental agencies and organizations that contribute resources for the sustainable operation and modernization of the Global Geodetic Observing System. The purpose of the GIAC is to provide a forum for coordinating and supporting the development, implementation, and operation of those components of the IAG's Global Geodetic Observing System, whose geodetic infrastructure is operated by governmental institutions. The GIAC is a forum that seeks to generate a unified voice to communicate with governments and intergovernmental organizations (Group on Earth Observations, United Nations bodies), and ensures that appropriate resources are allocated for all matters of global and regional spatial reference frames and GGOS research and applications.

*NASA's Role in GGOS new Organization—*In 2011, the IAG Executive Committee elected a new Chair of GGOS and adopted a new structure (Figure 3.2-1). This new structure is currently being implemented by GGOS and we expect that NASA will continue to play a leading role in the governance and activities of GGOS in the future.

*NASA-led GGOS Strategic Workshop—*In June 2012, GGOS conducted its Frankfurt strategic workshop, led by a NASA-appointed facilitator. The output of the workshop consisted of a series of objectives and supporting activities that meet the goals established by the GGOS board at an earlier retreat, also facilitated by a NASA representative in Zurich in February 2011.

*NASA-organized Upcoming GGOS Meeting—*NASA is organizing the upcoming GGOS meeting in San Francisco, California. At this meeting, NASA will propose a *project framework* (similar to NASA's 7120.5E) for the formulation, development, and deployment of GGOS. The activities identified in the Frankfurt workshop will be carried under this framework. It is anticipated that the use of a project framework similar, if not identical, to that used by the Space Geodesy Project will enable the seamless integration of the Space Geodesy System and Global Geodetic Observation System. This will be used to leverage additional partnerships within GGOS to meet next generation space geodesy objectives for the future of the realization of the terrestrial reference frame.

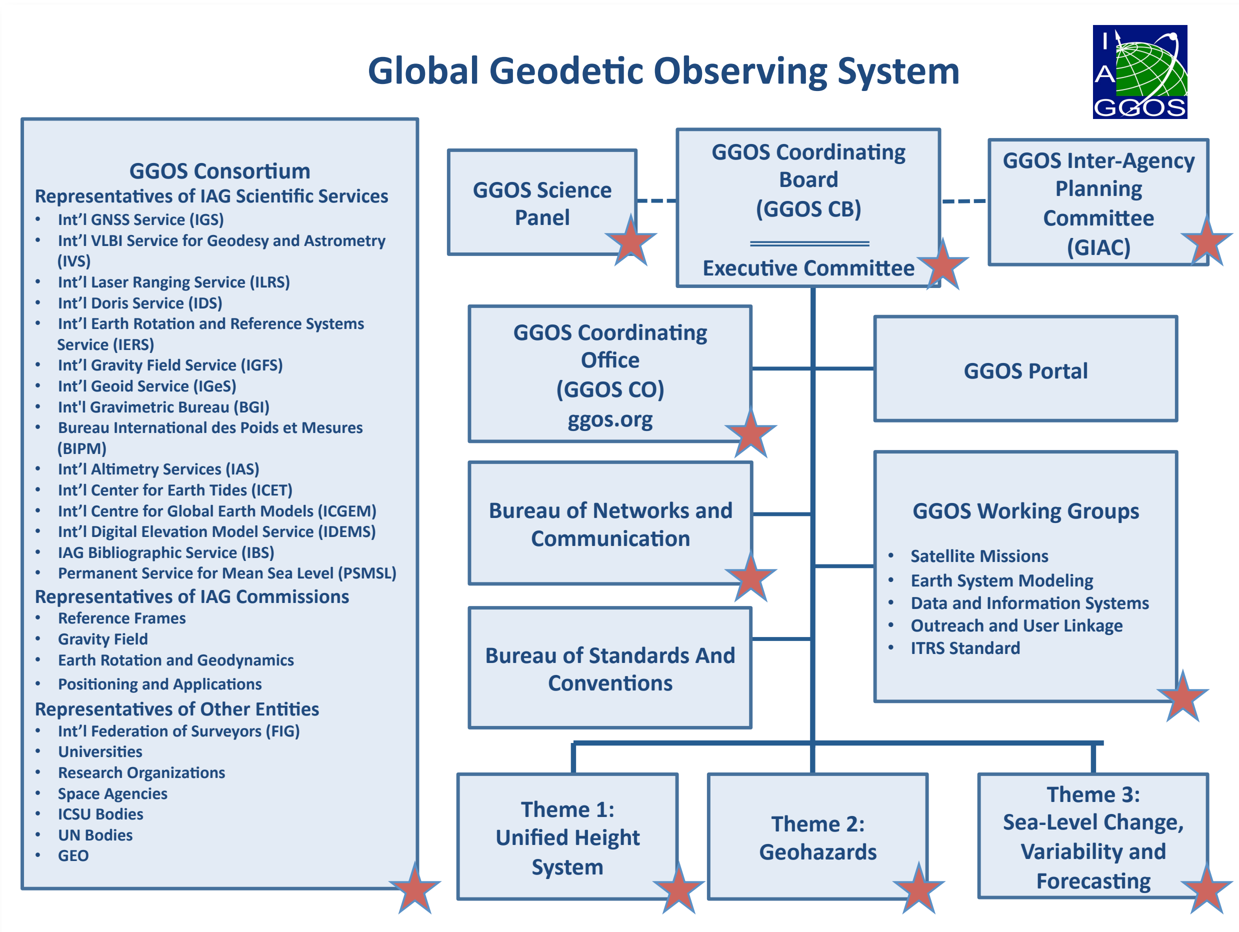


Figure 3.2-1: GGOS Organizational Chart. Red stars denote areas of NASA's contribution.

- **Space Geodesy Project**

SGP, NASA's key Contribution to GGOS—The Space Geodesy Project (SGP) is NASA'S key contribution to the new global observation system formulated under GGOS (see text box on previous page). It is expected that SGP will be one of the key projects that will act as a trailblazer to illustrate how a next-generation geodetic observation system can move from formulation to reality. This includes the utilization of next-generation observing instruments as discussed in Section 3.2.2. NASA-led efforts are under way to ensure the coordination and integration of SGP and the GGOS project.

Bilateral Meetings and Agreements—SGP serves as a platform to focus NASA's contributions to an international global space geodesy observation system and as a forum to channel an international dialogue aimed at collaboration. Table 3.2-1 shows the numerous bilateral meetings that have taken place recently. These NASA-led exchanges with the international community have lead to a number of cooperative agreements. These agreements are summarized in Table 3.2-2.

Table 3.2-1: List of Bilateral Meetings

County	Organization	POC	Meeting
Brazil	Instituto Nacional de Pesquisas Espaciais (INPE)	Eduardo W. Bergamini	- 8/13/10 Sao Paulo - 11/8/11 at NASA
Colombia	Instituto Geográfico Agustín Codazzi (IGAC)	William Martínez Díaz Elena Posada Dora-Inés Rey Martinez	- 11/10/10 Pachuca - 9/26/11 at NASA
Finland	Finnish Geodetic Institute (FGI)	Markku Poutanen Jarkko Koskinen	- 2/13/12 at NASA - 8/12 & 10/12 Operational site visits
France	Centre National d'Etudes Spatiales (CNES)	Richard Biancale Mandea Miora Andre Laurens	- 4/4-5, 2012 Paris
Korea, Republic of	Korea Astronomy and Space Science Institute (KASI)	James Park Hyung-Chul Lim	- 11/5/11 Daejeon - 11/18/11 at NASA
Norway	Norwegian Mapping Authority (NMA)	Ina Elsrud Line Langkaas Leif-Morten Tangen Per Erik Opseth	- 12/6/11 at NASA - 8/122 Operational Site visit
Taiwan	Institute of Earth Sciences Academia Sinica	Benjamin Chao Cheinway Hwang	8/9/11 Taipei
Russia	Institute of Applied Astronomy (IAA), Russian Academy of Science	Alexander Ipatov	9/24/12-9/28/12 St. Petersburg

Table 3.2-2: List of Bilateral Agreements Established

Country	Institution	Signature Date	Expiration Date
Armenia	National Survey for Seismic Protection	4/25/08	1/26/13
Australia	Geoscience Australia	7/26/07	7/26/17
Brazil	Agência Espacial Brasileira (AEB)	4/8/10	4/30/20
Brazil	Agência Espacial Brasileira (AEB)	8/15/11	8/31/21
Colombia	Instituto Colombiano de Geología y Minería (INGEOMINAS)	9/18/07	9/18/17
Finland	Finnish Geodetic Institute	9/19/05	9/19/15
Kenya	Regional Center for Mapping of Resources for Development (RCMRD)	2/6/07	2/6/17
Israel	Survey of Israel	8/10/06	8/10/16
Japan	Japan Aerospace Exploration Agency (JAXA)	10/10/08	10/10/12
Korea, Republic of	Korea Astronomy and Space Science Institute (KASI)	11/15/10	6/30/15

Nigeria	National Space Research and Development Agency (NASRDA)	10/10/08	10/10/18
Norway	Norwegian Mapping Authority	4/27/11	12/31/20
Peru	Universidad Nacional de San Agustín	5/27/09	10/25/14
Russia	Russian Academy of Sciences (RAS)	2/8/12	8/31/21
Saudi Arabia	King Abdulaziz City for Science and Technology (KACST)	10/2/10	10/2/20
South Africa	Hartebeesthoek Radio Astronomy Observatory (HartRAO)	10/2/08	1/27/17
South Africa	Hartebeesthoek Radio Astronomy Observatory (HartRAO)	4/30/09	9/30/19
Tahiti	CNES/University of French Polynesia	12/21/07	2/27/13
Ukraine	Crimean Astrophysical Observatory	4/2/08	6/2/18

3.2.2 NASA's Geodetic Techniques and Geodetic Product Support

Specific geodetic techniques allow NASA to fulfill a number of objectives that are essential to its mission. These objectives and contributing activities include spacecraft orbit determination, terrestrial reference-frame realization, and geodetic hazards prediction and early warning.

National Research Center Recommendation

"The United States should continue to participate in and support the activities of the international geodetic services (IGS, ILRS, IVS, IDS, IGFS and IERS) by providing long-term support for the operation of geodetic stations around the world and by supporting the participation of U.S. investigators in the activities of these services."

[NRC's National Requirements, p. 7, p. 87, p.107.]

No single technique is capable by itself to provide all the parameters needed to characterize the International Terrestrial Reference Frame in terms of origin, scale, and orientation. This characterization requires the combination of multiple techniques, such as Very-Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Global Navigation Satellite Systems (GNSS) and Doppler Orbitography by Radiopositioning Integrated on Satellite (DORIS). The following sections describe the NRC's recommendations, or objectives, regarding these techniques and NASA's activities in support of these objectives.

IERS

The primary objectives of the IERS are to serve the astronomical, geodetic and geophysical communities by providing the following:

- The International Celestial Reference System (ICRS) and its realization, the International Celestial Reference Frame (ICRF).
- The International Terrestrial Reference System (ITRS) and its realization, the International Terrestrial Reference Frame (ITRF).
- Earth orientation parameters required to study earth orientation variations and to transform between the ICRF and the ITRF.
- Geophysical data to interpret time/space variations in the ICRF, ITRF or earth orientation parameters, and model such variations.
- Standards, constants and models (i.e., conventions) encouraging international adherence.

Source: IERS Website

3.2.2.1 NASA's Support of the International Earth Rotation and Reference Systems Service (IERS)

National Research Center Recommendation

"The United States, through the relevant federal agencies, should make a long-term commitment to maintain the International Terrestrial Reference Frame (ITRF) to ensure its continuity and stability. This commitment would provide a foundation for Earth system science, studies of global change, and a variety of societal and commercial applications."

[NRC's National Requirements, p. 7, p. 107.]

NASA's Activities in Support of this Objective

NASA's Leadership Role in IERS—NASA has had an important role in the International Earth Rotation and Reference Systems Service (IERS) (see text box) through the participation of NASA or NASA-supported personnel on the IERS directing board, product centers, and working groups as illustrated in Figure 3.2-2. Current people include the IERS Directing Board Chair, C. Ma (NASA); IERS Directing Board members: F. Lemoine (NASA), E. Pavlis (University of Maryland), T. Herring (MIT) and S. Fisher (NASA); Global Geophysical Fluids Center's Special Bureau for the Oceans Chair, R. Gross (NASA); IERS Working Group on Site Survey and Co-location members: C. Abbondanza (NASA), J. Long (NASA), and M. Pearlman (SAO); IERS Working Group on Combination at the Observation Level member, R. Gross (NASA); IERS/IVS Working Group on the Second Realization of the ICRF Chair, C. Ma (NASA) and members: C. Jacobs (NASA) and O. Sovers (NASA); IERS Working Group on SINEX Format members: T. Herring (MIT) and E. Pavlis (University of Maryland); and IERS Working Group on Site Coordinate Time Series Format members: T. Herring (MIT), E. Pavlis (University of Maryland), and X. Wu (NASA).

NASA is making its long-term commitment to the realization of the ITRF through this involvement with the IERS. It is important to note that the benefits of the IERS to NASA are common with the general scientific community and society at large. Benefits in particular include the use of the ITRF to relate measurements in space and time on the Earth; the use of Earth orientation parameters, especially UT1 for precision orbit determination and spacecraft navigation; and the use of the International Celestial Reference Frame (ICRF) to relate phenomena and positions in the sky, as well as the basis for planetary ephemerides and related interplanetary navigation. The IERS is also the focus for the continued refinement and improvement of the ITRF, ICRF, and Earth orientation; which are all needed to support NASA scientific investigations.

The activities of the IERS include the coordination of analyses and generation of products by specific IERS components, as well as the establishment of standards and conventions. The ongoing Earth-Orientation-Parameters (EOP) series (long-term, rapid and predicted) are derived from the various space geodetic techniques where NASA participation is significant in data acquisition, analysis, distribution, and archiving. Similarly, the ITRF updates rely on all the aforementioned techniques, with the goal of having the next ITRF (ITRF 2013) available in 2014.

The ICRF is derived from VLBI data alone, and is subsequently linked to the next ICRF. EOP and ITRF products are also generated by non-NASA IERS components, albeit with NASA-collected data, while the ICRF work has been led by NASA through its role in VLBI and the IVS. Through these leadership efforts, NASA is making a commitment to deliver EOP and a realization of the ITRF as part of its contributions to the IERS.

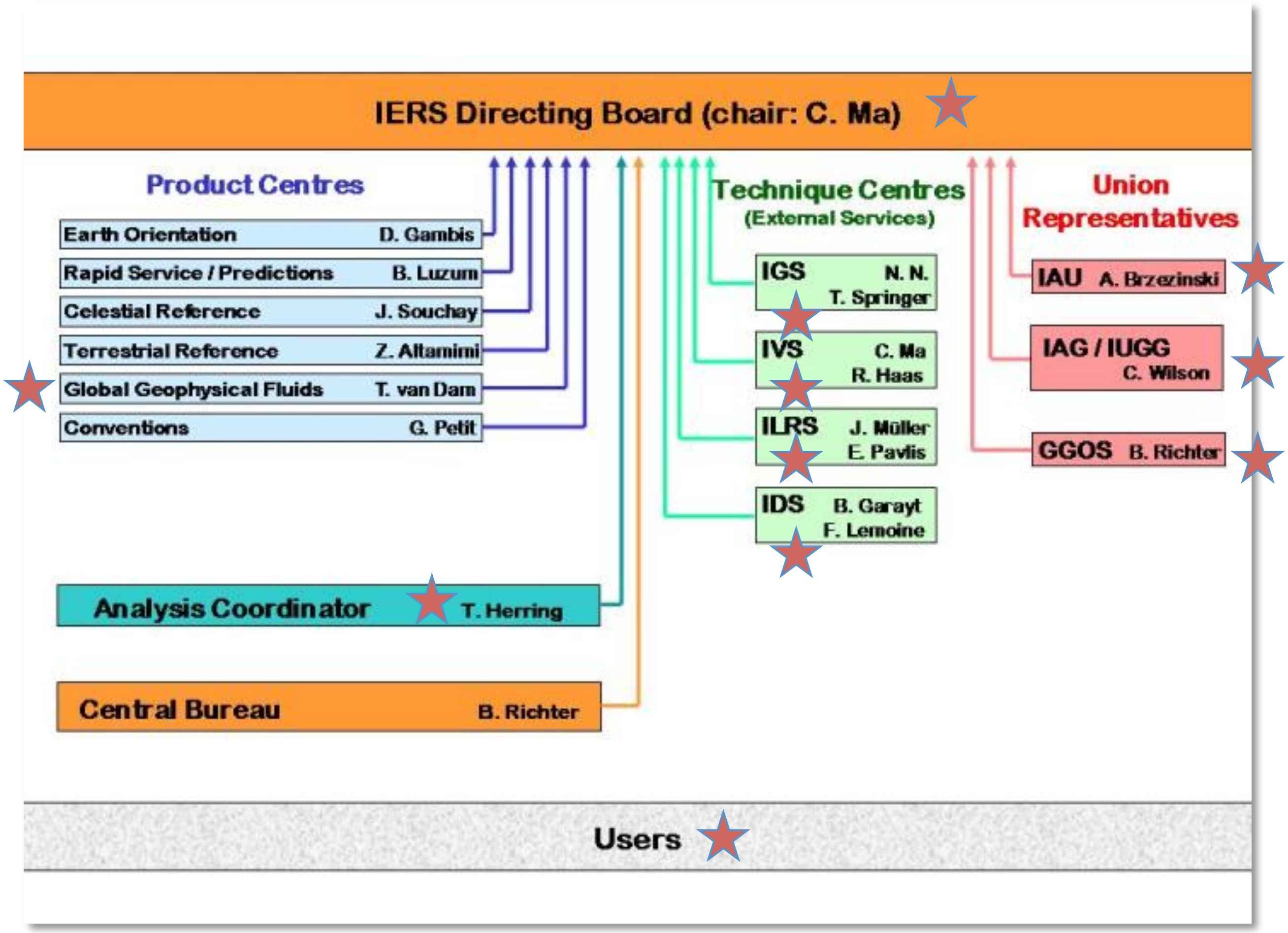


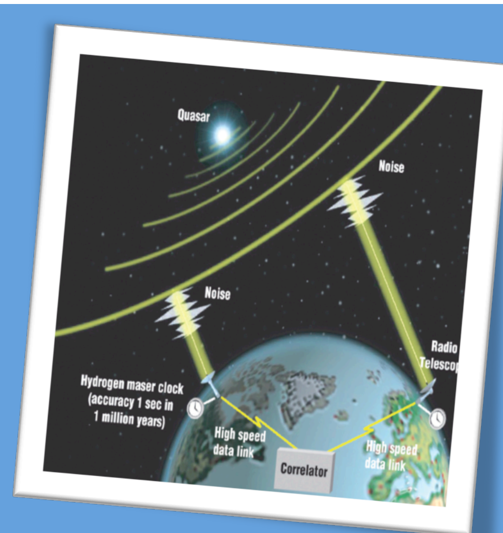
Figure 3.2-2: International IERS Service Organizational Chart. Red stars denote areas of NASA's/US contribution.

3.2.2.2 Very Long Baseline Interferometry (VLBI)

National Research Center Recommendation

"…. It also should install the next-generation VLBI systems at the four U.S. VLBI sites: Greenbelt, Maryland; Fairbanks, Alaska; Kokee Park, Hawaii; and Fort Davis, Texas. Maintaining the long history of data provided by these sites is essential for reference frame stability as we transition between ever-evolving geodetic techniques."

[NRC's National Requirements, p. 5.]



VLBI

The VLBI technique uses multiple radio telescopes to measure natural radiometric noise from distant radio sources, such as quasars. The differences in the arrival time for the same radio noise at separate antennas are later correlated to determine the time delay between the two antennas to millimeter precision. By observing radio sources in multiple directions, the VLBI network can be used to determine Earth's geometric shape and orientation in space.

Source: NRC's National Requirements.

"To pursue these system enhancements, the United States should invest in the following future developments to make VLBI more effective and less expensive:

(1) Radio telescope apertures should be reduced (to 10-12 meters) by increasing the recorded signal bandwidth. The benefits of smaller telescope apertures include: lower manufacturing and maintenance cost; higher attainable slew rates; lower instrument distortions associated with temperature changes and gravitational and wind loading; increased ease of locating the effective reference point; and reduced cost of piers and domes at observing stations. The optimal radio telescope parameters for geodetic applications are different than those for astronomical applications. The geodetic infrastructure must, therefore, include a dedicated network of geodetic VLBI observatories to obtain continuous measurements. In addition, using multiple VLBI antennas at some locations may yield improvements in accuracy and lead to better separation of atmospheric delay and clock parameter estimates. Although there is a need for a VLBI network dedicated to geodetic applications, correlator centers can efficiently process both geodetic and astronomic VLBI observations, and it appears that both communities can and should collaborate on the development of future generations of VLBI instrumentation.

(2) VLBI observations should be transferred from the observing stations to the correlator center(s) using high-speed communication systems. A small, but growing, number of VLBI sites are already using high-speed communication systems to transfer data. Using electronic data transfers can reduce the delays in processing "e-VLBI" observations to hours. Shorter delays would reduce the dependence on prediction models for determining the Earth's orientation, which is particularly important for deep space tracking and military uses. New correlator designs, possibly including

widely-distributed correlators rather than a single, central location, as well as more automated data processing may be required to handle the anticipated higher data rates.

(3) VLBI data processing and products are not well integrated into geodetic products generated by other systems, though integrated products could improve the accuracy of VLBI results. VLBI data analysis centers should consider using products from GNSS/GPS data analyses, such as polar motion and atmospheric delay estimates, in the generation of VLBI products. The combined analysis would aid in terrestrial reference frame realization using VLBI networks with a small numbers of sites. The multi-look angles available with GNSS/GPS observations also could assist in accounting for atmospheric delays in VLBI processing, and the combined analyses would aid in integrating the VLBI analysis centers into the GNSS/GPS community."

[NRC's National Requirements, pp. 69-70.]

NASA's Activities in Support of this Objective

Continuing NASA's Leadership role in VLBI—Geodetic and astrometric VLBI activities on global and regional scales are organized through the International VLBI Service for Geodesy and Astrometry (IVS)—an international collaboration of institutions that operate or support VLBI components. The IVS currently consists of around 80 permanent components, which are supported by 41 full-member organizations and six affiliated organizations spanning 20 countries.

NASA has traditionally taken a leadership role in organizing and supporting the activities of the VLBI service, driven by the fact that the geodetic VLBI technique was spearheaded and organized by NASA. Within the VLBI service, NASA provides the functions of several permanent components such as: Network Stations, an Operation Center, an Analysis Center, and a Technology Development Center. Its predominant role within the service today, however, is derived from the provision of the Central Bureau (Coordinating Center), the Network Coordinator, and the NASA-supported development of the next generation VLBI system, dubbed VLBI 2010. The Coordinating Center is staffed with NASA's D. Behrend as director, and is supported by NASA personnel C. Thomas (Operation Manager), K. Baver (General Programmer and Editor), and F. Gomez (Web Manager). The Crustal Dynamics Data Information System (CDDIS) is one of the data centers supporting the service providing access to IVS data and products. NASA's contributions to the IVS are illustrated in Figure 3.2-3.

The IVS Coordinating Center is responsible for the coordination of both the day-to-day and the long-term activities of the IVS; consistent with the directives and policies established by the IVS Directing Board. Its primary functions include: coordinating observing programs, maintaining the master schedule of observing sessions, fostering communications, developing standards for IVS components, providing training in VLBI techniques, organizing workshops and meetings, producing and publishing reports, maintaining the IVS information system, and providing the secretariat of the IVS Directing Board. The Network Coordinator, E. Himwich, works closely with the Coordinating Center and is responsible for the maintenance of a high quality level of station operation and data delivery. In particular, he monitors the adherence to standards, participates in the quality control of the data acquisition performance of the stations, tracks data quality and data flow problems, and suggests actions to improve the level of performance. The Network Coordinator takes a leading role in ensuring the visibility and representation of the VLBI network.

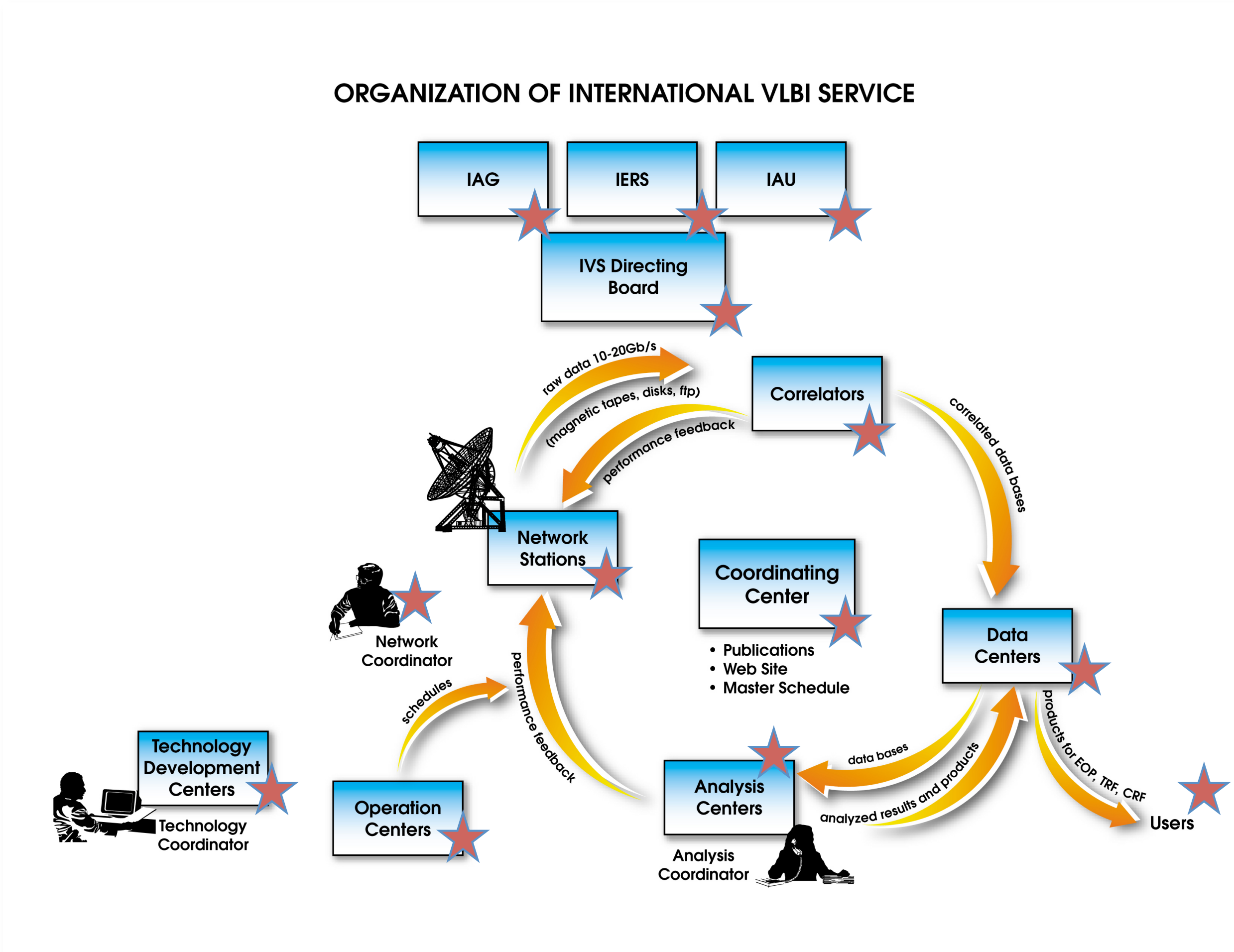


Figure 3.2-3: International VLBI Service Functional Chart. Red stars denote areas of NASA's contribution.

NASA's Next-generation VLBI— NASA is a key participant in the IVS, and is leading the development of the next-generation VLBI under the aegis of SGP, in response to the shortcomings of the current aging VLBI systems as well as in direct response to the NRC recommendations. This next-generation VLBI, called VLBI 2010, will replace the current system over the next several years. NASA is contributing significantly to the technological development of the system, which is mostly being performed by the MIT Haystack Observatory. These efforts include the development and deployment of electronic VLBI (e-VLBI) as recommended by the NRC.

In the organizational structure of the IVS, NASA personnel occupy key positions in the respective bodies responsible for the VLBI 2010 development and implementation: NASA's C. Ma and D. Behrend are members of the IVS VLBI 2010 Committee (V2C) for technical development as well as of the IVS VLBI2010 Project Executive Group (V2PEG) for strategic planning. In addition, NASA's E. Himwich, C. Ma, and D. Behrend are IVS Directing Board members taking influence on the general policies the IVS is pursuing. The next several years will see the development of the next VLBI system to come to fruition with its deployment in the field; aligning the effort with the Space Geodesy Project and GGOS objectives. It is anticipated that the deployment of VLBI 2010 will include, in direct response to the NRC recommendation: Greenbelt, Maryland (together with the Westford, Massachusetts site, constitutes the prototype VLBI 2010 baseline); Fairbanks, Alaska; Kokee Park, Hawaii; and Fort Davis, Texas. The development work performed on the baseline between Goddard and Westford will be instrumental for this effort. Furthermore, the aforementioned sites will be part of the VLBI2010 Global Observing System (VGOS), a global network of new fast radio telescopes and high capacity data acquisition systems optimized for Earth orientation and the terrestrial reference frame. VGOS was recently launched by the IVS and will be the VLBI component of the GGOS.

International Coordination—The two aforementioned committees (V2PEG and the V2C), with their NASA participants, are engaged in promoting and coordinating the VLBI 2010 activities in international forums. On of these forums was the 1st International VLBI Technology Workshop held at Haystack Observatory in Massachusetts in October 2012. Major upcoming forums for presenting results and coordinating efforts with international experts and stakeholders are the IVS Technical Operations Workshop (TOW) and the IVS General Meeting (GM), both anticipated to take place in Spring 2014 at Haystack Observatory in Massachusetts and in Shanghai, China respectively. In support of these efforts, NASA personnel, such as C. Ma, participate in both SGP and GGOS meetings to ensure the integration of VLBI 2010 with the next-generation geodetic observation systems.

3.2.2.3 Laser Ranging

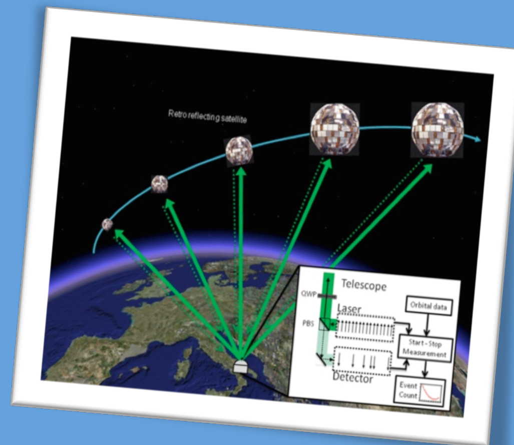
National Research Center Recommendation

"In the near term, the United States should construct and deploy the next generation of automated high-repetition rate SLR tracking systems at the four current U.S. tracking sites: Haleakala, Hawaii; Monument Peak, California; Fort Davis, Texas; and Greenbelt, Maryland."

[NRC's National Requirements, p.5 & p. 104.]

"The United States should make a long-term commitment to deploy a new generation of SLR tracking stations capable of high-precision, high-rate, eye-safe, autonomous operation. At a minimum, these next-generation SLR tracking stations should be deployed at the four current United States tracking sites (Haleakala, Monument Peak, McDonald Observatory, and Greenbelt) to retain and extend the value of these sites for long-term terrestrial frame determination. International cooperation to improve the geographic coverage of the global SLR network and maximize the value of the U.S.-operated sites is also recommended."

[NRC's National Requirements, p. 76.]



SLR & LLR

In these techniques, Satellite Laser Ranging (SLR) and Lunar Laser Ranging (LLR), a laser signal is transmitted from a ground-based station, reflects off specially designed mirrors (retro-reflectors) placed on artificial satellites (SLR) or on the moon (LLR), and is received back at the station. Satellites and the moon orbit the Earth due to the Earth's gravitational pull. This technique therefore provides a unique connection between the Earth's surface and its gravity field, which reflects the distribution of mass deep within the planet.

Source: NRC's National Requirements.

NASA's Activities in Support of this Objective

NASA's Laser Ranging Leadership Role—NASA continues to be a leader in the International Laser Ranging Service (ILRS) community— NASA's John Degnan led the formation activity of the ILRS and was its first Governing Board Chair. Figure 3.2-4 illustrates NASA's extensive contribution to the ILRS, including operating the ILRS Central Bureau with M. Pearlman as Director and C. Noll as Secretary. E. Pavlis (University of Maryland) is the chair of the Analysis Working Group; J. McGarry (NASA) is one of the co-chairs of the Transponder Working Group. These Working Groups provide the expertise to address technical and operational issues whose resolution is essential to improved data products for the users. In addition, NASA supported personnel are active in all of the working group activities; five NASA-affiliated personnel (D. McCormick, J. McGarry, E. Pavlis, C. Noll, and M. Pearlman) hold positions on the sixteen-member governing board. Additionally, E. Pavlis (University of Maryland) is the Technique Analysis Coordinator as well as the ILRS representative on the IERS Directing Board, which typically meets twice a year. Finally, the CDDIS is one of two data centers providing archive and distribution support to ILRS.

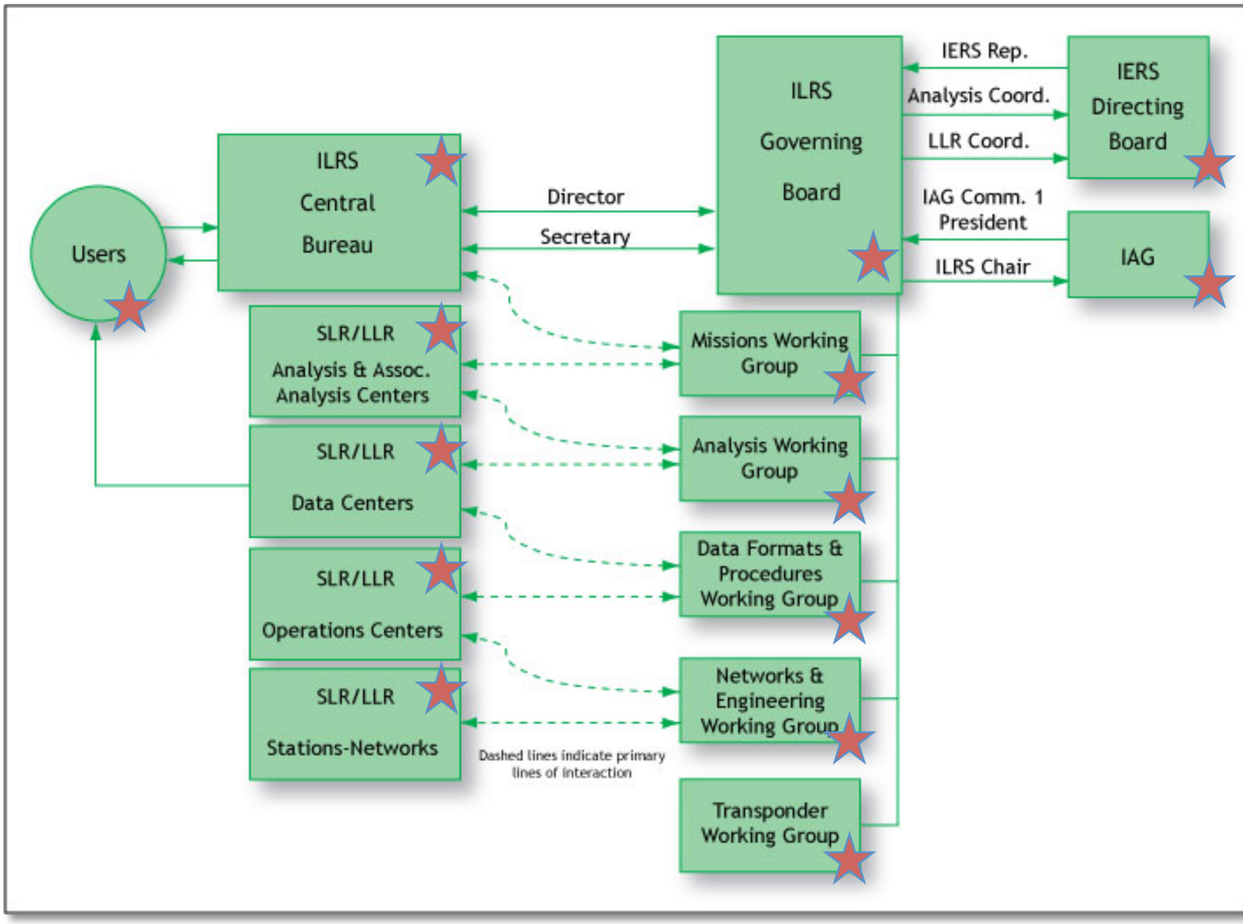


Figure 3.2-4: International Laser-Ranging Service Functional Chart. Red stars denote areas of NASA's contribution.

NASA's Next-generation SLR—NASA (GSFC) is leading the development of the next-generation SLR technology under SGP. This so-called "Next Generation SLR" is aligned with the NRC recommendation cited above. Furthermore, as part of SGP and NASA's involvement on GGOS, a number of next-generation stations are being considered for deployment. These could include stations at Haleakala, Hawaii; Monument Peak in California; McDonald Observatory in Texas; and Greenbelt, Maryland, where the prototype is being developed.

International Coordination—NASA, through its involvement in the ILRS, SGP, and GGOS, is encouraging the international community to develop and deploy similar next-generation SLR technology that will allow meeting the new objectives of ITRF accuracy and stability, in response to the above-cited NRC reports. Some of NASA's current activities supporting this international coordination are:

- ILRS Governing Board meetings with accompanying working group meetings in the Spring and Autumn of each year, concurrent with other international meetings;

- Specialized laser workshop on retroreflector array at the INFN (Istituto Nazionale di Fisica Nucleare) at Frascati, Italy, November 2012;
- International Workshop on Laser Ranging (held on a bi-annual basis) in Tokyo, Japan, December 2013;
- EGU, AOGS, and AGU meetings in April, August, and December respectively; including splinter meetings with participating groups for ILRS and GGOS activity;
- Specialized laser workshop celebrating the 50th anniversary of the first satellite laser ranging observations at NASA GSFC in October 2013. In addition, NASA conducts monthly ILRS Central Bureau meetings where the full activity of the ILRS is reviewed and necessary actions are delegated.
- The Analysis Working Group (AWG) will held one of its two meetings at NASA Goddard on October 2013.
- NASA personnel associated with the ILRS, and other services, will participate in the quadrennial IAG meeting in Postdam, Germany in September 2013, which commemorates the 150th anniversary of the IAG.

3.2.2.4 Global Navigation Satellite Systems (GNSS)

National Research Center Recommendation

"The United States should establish and maintain a high-precision GNSS/GPS national network constructed to scientific specifications, capable of streaming high-rate data in real-time. All GNSS/GPS data from this network should be available in real-time without restrictions (and at no cost or a cost not exceeding the marginal cost of distribution), as well as in archived data files."

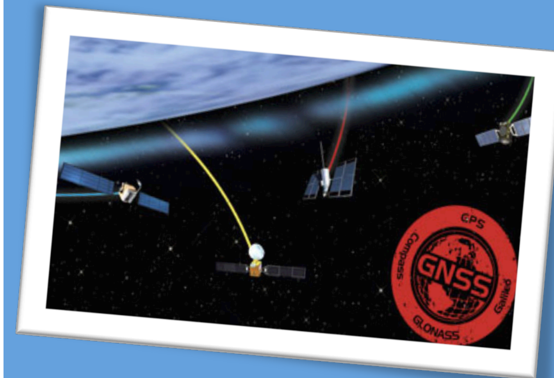
[NRC's National Requirements, p. 6 & p. 105.]

"The United States should significantly strengthen the GPS network by upgrading the instrumentation, monumentation, and technology. In addition, there should be greater coordination among the various U.S. agencies to develop strategies for meeting the needs of multiple agencies, as well as for long-term site maintenance, upgrade, dataflow, and response to technological innovation."

[NRC's National Requirements, p. 73.]

"Recognizing the importance of data-processing capabilities and activities to the national interest, the United States should continue to support these real-time, high-precision operations with a long-term view (not only for research and development)."

[NRC's National Requirements, p. 73.]



GNSS

GNSS is a generic term for satellite navigation systems that provide autonomous spatial positioning with global coverage. The U.S. NAVSTAR Global Positioning System (GPS) falls into this category; other countries also have or are developing GNSS systems. Coded signals transmitted from multiple satellites and received by multiple GNSS receivers allow time delay, and indirectly distance, measurements between the satellites and GNSS receivers. Although GNSS/GPS is designed to be accurate to the meter level, geodesists have determined how to use these signals to achieve accuracies 1,000 times better. The strength of these systems lies in the low cost of the ground-based systems (the systems do not include satellites) compared to VLBI or SLR/LLR. GNSS, therefore, provides a geographic coverage unequaled by these other systems because they can be inexpensively deployed and have a wide range of applications.

Source: NRC's National Requirements.

NASA's Activities in Support of this Objective

NASA's GNSS Leadership Role—NASA is recognized as a key global leader in GNSS. Components of the IGS that NASA supports are highlighted in the organization chart shown in Figure 3.2-5.

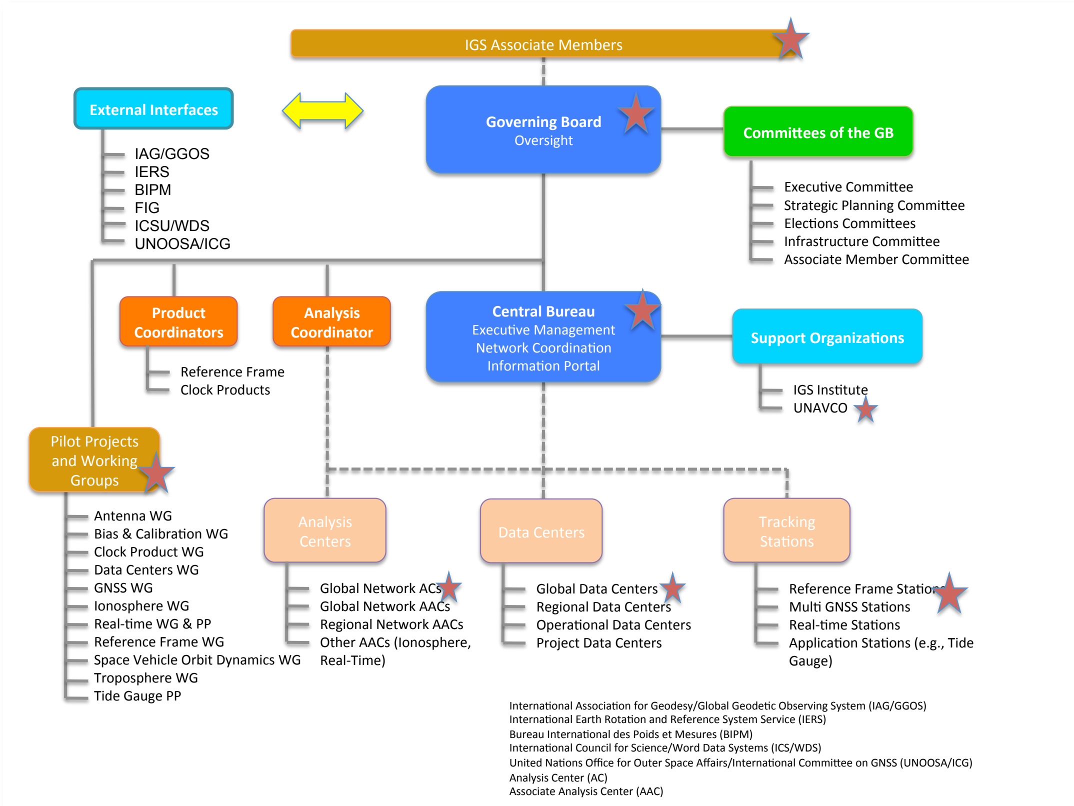


Figure 3.2-5: International GNSS Service Organizational Chart. Red stars denote areas where NASA makes contributions.

NASA's contributions to GNSS include:

- Data from the Global Geodetic Network (GGN) managed at JPL under the leadership of NASA's D. Stowers. GGN fields over seventy high-quality stations and contributes these to the IGS as a robust component of the IGS 400-strong network of stations;
- Support for the IGS Central Bureau (IGSCB) coordination office, hosted at NASA JPL in Pasadena, California. This is the executive arm of the IGS International Governing Board, and supported by NASA's R. Neilan (IGSCB Director), S. Fisher, R. Kachikyan & G. Walia;
- Support, jointly with the National Science Foundation, of the GPS facility at UNAVCO in Boulder, Colorado, that supports NASA GGN engineering and the Central Bureau data system and network engineering;
- A leading IGS Analysis Center at NASA JPL lead by S. Desai & D. Murphy;
- Premier Global Data Center at GSFC, the CDDIS, lead by NASA's C. Noll (as it is the case for other services);
- Approximately one in ten of the current 180 IGS Associate Members, which are the electing body to the IGS Governing Board;

- Four current members of the IGS governing board, namely NASA's S. Desai, S. Fisher, R. Neilan and C. Noll;
- Five former members of the IGSGB, namely, NASA's Y. Bar-Sever, W. Melbourne, A. Moore, M. Watkins & J. Zumberge.

IGS's GNSS Real-Time Service— In alignment with the NRC recommendation, the IGS is undertaking upgrades of its system elements to provide multi-GNSS real-time data and products at no cost to its users. This is very much aligned with NRC and NASA supported GGOS objectives regarding the so-called "geo-hazard theme." This theme seeks to use real-time GNSS data and products for geodetic hazards, such as earthquakes and tsunamis, thereby enabling early warning, mitigation, response, and damage assessment. This new IGS service is expected to be fully operational in 2013. The leadership of the NASA-funded IGS Central Bureau continues to be instrumental in the coordination of efforts for this initiative.

*IGS's Multi-GNSS Services—*Also in alignment with the NRC recommendation, the IGS has undertaken the collection of data from multiple GNSS systems. This initiative, named M-GEX for Multi-GNSS Experiment, represents the evolution of the IGS network and processes to include all GNSSs. Currently IGS includes the United States's GPS and Russia's GLONASS. This experiment is intended to demonstrate a new state-of-the-art network that tracks all modernized GPS and GLONASS, as well as China's Beidou/Compass, Europe's Galileo, Japan's QZSS and India's IRNSS. This is a major experimental undertaking that was initiated in Feb 2012. Once again, the leadership of the NASA-funded IGS Central Bureau has been instrumental in advancing this objective.

3.2.2.5 DORIS

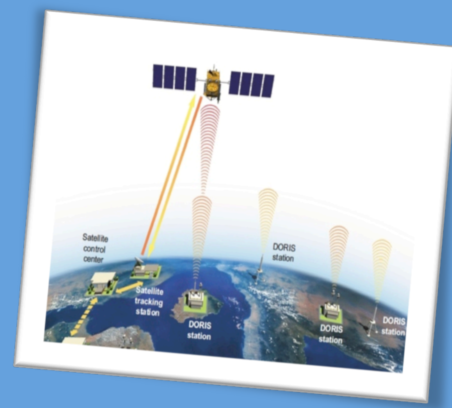
National Research Center Recommendation

"The United States should deploy, where possible, DORIS receivers on U.S. low-Earth orbiting missions to enhance the DORIS positioning performance and the contribution of DORIS to the ITRF."

[NRC's National Requirements, p. 77.]

NASA's Activities in Support of this Objective

NASA's DORIS Leadership Role—NASA's participation in DORIS is illustrated in Figure 3.2-6. The following NASA personnel serve on the Governing Board of the IDS: C. Noll (NASA), who serves as Data Flow Coordinator; F. Lemoine (NASA), who serves as Analysis Coordinator, and C. Ma (NASA GSFC), who serves as the IERS representative. The NASA CDDIS (Crustal Dynamics Data Information System) acts as one of the international data centers for the IDS, a role that the CDDIS also plays for the other geodetic techniques. In the context of the Space Geodesy Project, NASA-supported personnel are evaluating the radio-interference environment at the NASA prototype station at the Goddard Geophysical Astronomical Observatory (GGAO). This includes assessing how the VLBI systems can be affected by both the SLR aircraft protection radar and the DORIS beacon, and how advanced system design can allow all techniques to operate together at a four-technique geodetic site.



DORIS

The Doppler Orbitography and Radiopositioning Integrated (DORIS) consists of a network of terrestrial beacons that transmit signals to instruments onboard a satellite including an antenna, radio receiver, and an ultra-stable oscillator that provides the reference frequency standard. The onboard receiver compares the signal emitted by the ground beacon against the onboard frequency standard. Because of the satellite's velocity, the incoming signal will appear to be shifted in frequency causing a "beat" with respect to the satellite's internal clock. Measurements of the number of beat cycles can be used to determine the velocity of the satellite, which is then incorporated with satellite orbit dynamics to determine the distance between the satellite and the ground beacon. DORIS is optimized for precise orbit determination with global coverage and all-weather measurements. DORIS has been part of the activities of the International Earth rotation and Reference systems Service (IERS) since 1994.

Source: NRC's National Requirements.

As of March 2012, four DORIS stations are located in the United States, and two are presently co-located at NASA or NASA-related facilities with other geodetic techniques: Greenbelt, Maryland (GGAO), and Kauai, Hawaii (Kokee Park). The other two stations are located at Cold Bay, Alaska, and in Miami, Florida. A fifth station awaits final clearance for re-installation at the Goldstone Deep Space Network (DSN) tracking site in Goldstone, California (DSS13), a site occupied by DORIS from 1988 to 2004. Furthermore, the IDS is considering the installation of another station at the US territory of Wake Island, in the North Pacific. NASA, through the office of the NASA GSFC Spectrum Manager, applies for frequency authorizations for each of the United States DORIS sites, and coordinates with external entities to avoid frequency impingements between DORIS and commercial services. NASA also supplies advice on the installation of new DORIS stations.

For example, the installation of the DORIS station at Cold Bay followed a long search to find a new host for an Alaskan station to replace the previous site at Fairbanks, where site support by the host agency ended in 2010. The US DORIS stations supply critical geographic tracking coverage to the DORIS system, and especially to the NASA/CNES ocean radar altimetry satellites such as TOPEX/Poseidon, Jason-1, and Jason-2.

NASA's role in the analysis of DORIS data extends back to 1990, when DORIS data from SPOT-2 was analyzed for inclusion in the JGM-1 and JGM-2 Earth geopotential models. These models were pre- and post-launch gravity models, developed at the start of the TOPEX/Poseidon mission to minimize the orbit error induced by the geopotential on altimetry data products. The orbits used on the TOPEX/Poseidon mission geophysical data records (GDRs) were computed at NASA GSFC (1992-2006). NASA GSFC has been an accepted POD analysis center for Jason-1 and Jason-2, participating in the Ocean Surface Topography Science Team. NASA GSFC has also supplied updated orbits to the scientific community based on analysis of DORIS, SLR, and GPS data; the implementation of GRACE-gravity models; other IERS-model updates; and the new terrestrial reference frames, ITRF2005 and ITRF2008.

NASA GSFC is an accepted analysis center of the IDS, and contributed a full time series of SINEX solutions (1993-2008) for inclusion in ITRF2008. Since the release of ITRF2008, it has continued to submit SINEX solutions, maintaining its participation in the Operational IDS Combination. NASA GSFC has participated routinely in the IDS Analysis working group (AWG) activities since 2008.

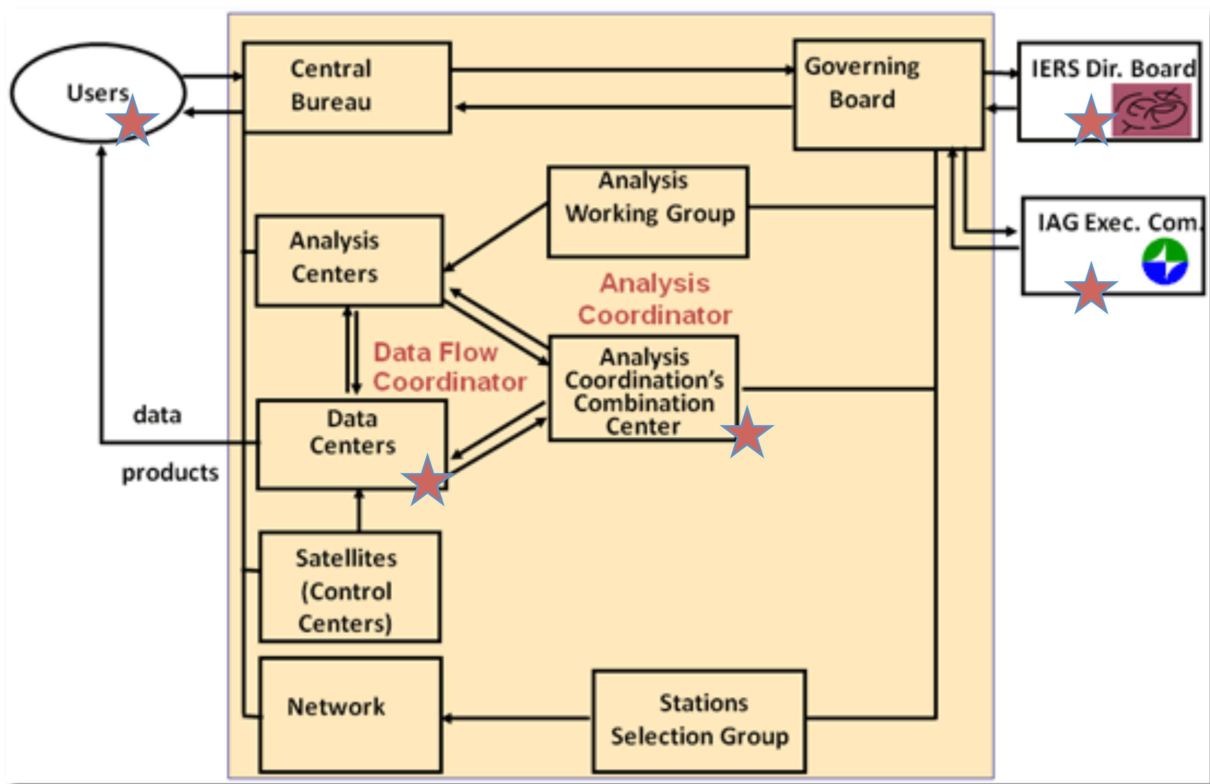


Figure 3.2-6: International DORIS Service Functional Chart. Red stars denote areas of NASA's contribution.

*Increasing the number of DORIS receivers on NASA missions—*The number of DORIS user satellites that supply DORIS data has expanded from only two or three in the 1990s (TOPEX/Poseidon, SPOT-2, SPOT-3) to seven satellites in 2011. The latest satellites (Jason-2, Cryosat-2, HY-2A) employ the DGXX receiver, which can track up to seven ground beacons simultaneously. New joint European-American missions, such as Jason-3, Jason-CS, SWOT (Surface Water & Ocean Topography) will carry DORIS receivers in direct alignment with the NRC recommendation. Along these strategic lines, NASA is also encouraging the development of a modification of the GPS/TRIG receiver to also track DORIS, in order to support on-orbit colocation between the geodetic techniques. Integrated with this effort is NASA's support of the establishment and maintenance of DORIS stations in the U.S. and its territories, to assure adequate geographic coverage for satellites with DORIS receivers—including ocean radar altimeter satellites that have NASA interest or participation. This support also includes the establishment of a prototype next generation station that includes DORIS, thus developing strategies to assure successful cohabitation by all the geodetic techniques.

4.0 Acknowledgments

The following NASA-affiliated personnel contributed to this effort:

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